LINKING FIRE BEHAVIOR TO ITS EFFECTS ON LIVING PLANT TISSUE[1]

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ABSTRACT.--Various measures of fire intensity
have been used to correlate fire behavior with fire
effects. The full array of fire impacts, however,
can only be meaningfully predicted by using several
of the commonly advocated fire behavior measures.
Selection of the proper descriptor to use is
dictated by whether the meristematic tissue in
question is located below, within, or above the
flames. The use and misuse of various intensity
estimates to assess fire damage are discussed.

Uniform fire behavior descriptors are mandatory
not only to correlate fire intensity with fire
effects but also to accurately predict the effects
of operational prescribed burns. However, the
attempted prediction of fire effects from fire
behavior descriptors that have little direct
correlation to the effect in question can be found
in the literature all too often. The results are
frequently counterproductive and simply tend to
further confuse an already unclear situation.
There is currently much discussion among fire
researchers regarding which items need to be
measured, let alone how they should be measured or
to what level of accuracy. The situation is not
hopeless, however. Several fire behavior
estimators have proven useful in describing the
relationship between fire behavior and effects and
provide a basis for comparison.

Intensity (heat per unit area per unit time) not
only describes the rate of heat release, but also
the rate at which heat is received by an object
such as a plant stem. The rate heat is received
will always be the lesser of the two, the magnitude
of the reduction dependent upon the distance
between the source and the receiver, and the
characteristics of the medium through which the
heat flows. The total amount of heat released,
rather than its rate of release, may be the
appropriate descriptor to use in many cases.

This paper will examine some aspects of fire
damage, define selected fire behavior descriptors,
and then suggest descriptors to use in the
assessment of belowground, ground level, and aerial
plant damage.

FIRE DAMAGE

Living plant tissue is killed when it is heated
to its lethal time-temperature threshold. This
combination ranges from almost instantaneous death
above 141^{0}F to slow death over a period of
several hours at temperatures in the neighborhood
of 120^{0}F (Hare 1961). Whether tissue will be
killed when a plant is subjected to fire depends
upon how well this tissue is protected and its
location in relation to the burning fuel. The
roots, stem, and crown of a plant can all be
severely impacted by fire, individually as well as
collectively.

Root Damage

The literature describing root damage associated
with fire, especially fires not involving activity
fuels (slash disposal), is limited--not because we
do not know how to measure the damage, but because
the excavation of root systems without destroying
the minute feeder roots is an exceeding y tedious
task. It is my opinion that fire-related root
damage is considerably more prevalent than commonly
thought. Although soil and duff provide excellent
insulation, feeder roots have no protective
covering of bark and often tend to be concentrated
near the soil surface, even colonizing the humus
layer as it develops in the interim between fires.

Geiszler and others (1984) related root mortality in lodgepole pine to the amount of charred bark. They reported that the probability of root-kill approached 100 percent when bark char was noticeable on more than 66 percent of a tree's basal circumference. Even when these low-intensity fires did not reach the trunk, up to 33 percent of the trees had fire-killed roots nonetheless. Several investigators (e.g., Redmond 1959) have related root mortality to insect-caused crown defoliation. I would expect this relationship to be even more pronounced to the extent that buds, twigs, and needles are all killed by a fire.

Bole Damage

Bole damage depends upon fire temperature, exposure time, and bark thickness. Flame temperatures are in the neighborhood of 1400°F and are independent of intensity and fire type.

Under prescribed underburning conditions, the total amount of heat energy impinging upon a plant base is probably about the same, whether from a headfire or backfire. Although headfires have a higher rate of spread, they also have a proportionately deeper (wider) flame zone; consequently, about the same amount of time is required for both headfires and backfires to pass a given point. Thus a tree bole will experience flame contact near ground level for the same time period regardless of whether the fire heads or backs. Head fires have longer flames and therefore tend to involve more understory fuels, but the additional energy produced is distributed over a proportionately larger area of the stem. From a practical standpoint, one can thus assume that a given location on a plant stem near its base will be subjected to about the same amount of heat. However, as flames lengthen under increasingly severe wildfire conditions, receptors in the path of the fire will receive a larger heat flux per unit area.

Bark thickness differs by species, is greatest at the tree base, increases with age, and is a function of vigor. The bark of rapidly growing trees thickens much faster than it does on slow-growing overtopped trees. Fire-sensitive species tend to have thin, moist bark. The thicker bark of fire-resistant species such as the southern pines is a poor heat conductor because the outer layer is corky and contains little moisture. Once southern pines reach a basal diameter of about 2 inches they are seldom killed by stem girdling alone.

Crown Damage

Crown scorch is the easiest damage component to visually measure and is an excellent indicator of a plant's postfire survival prospects in those species where the minimum heat needed to scorch the foliage also results in bud kill. In some species, such as the southern pines, ponderosa pine, and western larch, bud kill is generally much less severe than needle kill. The reasons for this differential response include the fact that the

buds may be shielded by the foliage, and that bud mass may be greater than needle mass which results in a higher heat capacity. Both of these factors lower the rate of temperature rise in the buds. Southern pines routinely survive 100 percent defoliation provided bud damage is not excessive. The key to determining bud mortality is crown consumption. The heat required to ignite foliage is more than three times the amount necessary to kill it. These higher temperatures are sufficient to kill the surrounding meristematic tissues as well, so the amount of crown consumption is an excellent indicator of crown kill.

FIRE BEHAVIOR DESCRIPTORS

Rather than attempt to record all the parameters that interact to produce fire behavior, observers tend to use a single descriptor that integrates the various input variables. Some descriptors are easy to observe and measure but others, such as fireline intensity and reaction intensity, are more difficult to visualize and cannot be directly measured.

Fireline Intensity

Fireline intensity, also known as either Byram's fireline intensity or frontal fire intensity, is perhaps the most often used descriptor. Even though the descriptor does not actually measure the intensity of the advancing fire edge as implied by its name (Tangren 1976), it is commonly used to compare fires and as a guide for assessing both the effectiveness of prescribed fire and the difficulty of wildfire containment. Fireline intensity is defined as the heat energy released per unit length of fire front per unit time regardless of the depth (width) of the flame zone (Fig. 1).
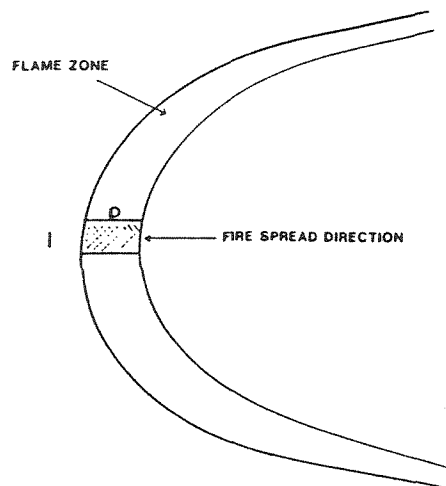

FIGURE 1.-- The crosshatched area of the fire front, 1 x D, releasing the energy calculated by Byram's fireline intensity equation (from Tangren 1976).

It is the product of the low heat of combustion, the weight of the fuel consumed in the flame zone, and the rate of fire spread (Byram 1959). The same output value can result from different values of the input variables. The low heat of combustion remains fairly constant so that for a given fireline intensity, a decrease in the forward rate of spread implies an increase in the amount of fuel consumed. Thus slow rates of spread will concentrate more heat on the lower portion of a tree bole. Alexander (1982) presents an in-depth discussion of the attributes of this descriptor.

Byram (1959) determined a mathematical relationship between fireline intensity and flame length, which allows one to visualize the flame front associated with a given fireline intensity. Nelson (1980) developed separate equations relating flame length to fireline intensity for headfires and for backfires.

In calculating both fireline intensity and reaction intensity (defined below), fuel consumption is confined to the moving flame zone. The value is less than total fuel consumption because of smoldering and intermittent flaming behind the flame front. This is especially true in headfires. As the fraction of the available fuel consumed after passage of the flame front increases, the overprediction of intensity will also increase. Smith and others (1983) compared fireline intensity values computed from flame length observations and from the product of the low heat of combustion, available fuel, and rate of spread on several small prescribed fires. They found the use of flame length gave consistently lower fireline intensity values which I suspect were due in part to the fact that fuel consumption continued behind the flame front.

Reaction Intensity

Reaction intensity, or combustion rate as defined by Byram (1959), is the rate of heat release per unit area per unit time in the flame zone (Fig. 2). This descriptor can be derived by dividing fireline intensity by the depth (width) of the flame zone. Again the same output value can be produced by varying the values of the input variables. Reaction intensity is calculated in Rothermel's (1972) fire spread model which, in turn, is used for fire behavior calculations in the National Fire Danger Rating System (NFDRS) and BEHAVE.

Flame Length

Flame length is defined as the distance between the tip of a flame and the ground, midway in the flame zone (Fig. 3). Flame length is readily observable but changes continually and is very difficult to accurately estimate. More reliable length estimates can perhaps be made by dividing observed values of flame height by the sine of the angle formed by the flame and the ground, or by the cosine of the angle formed between the flame and the vertical.
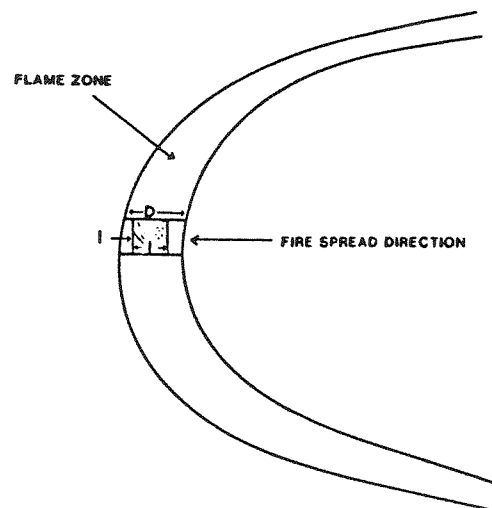

FIGURE 2.-- The area of the fire front, 1 X 1, releasing the energy calculated by the equation for reaction intensity.
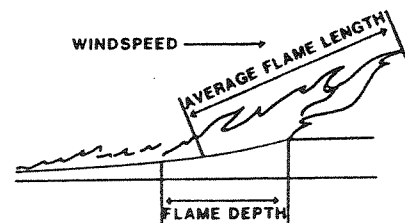

FIGURE 3.-- Flame characteristics shown for a wind-driven fire (adapted from Rothermel and Deeming 1980).

Heat Per Unit Area

The total amount of heat released per unit area during the time period that the unit area is in the flame zone can be calculated directly by multiplying the low heat of combustion by the amount of fuel consumed, or by dividing fireline intensity by rate of spread, or by multiplying reaction intensity by residence time. The amount of heat given off per unit area is thus simply a function of available fuel, but where this energy is released depends upon the dimensions of the flame envelope. Small flames will concentrate it near ground level while longer flames will release energy higher above the ground surface.

Residence Time

Residence time is defined as the length of time it takes the flame zone to pass a given point. Fuels with a high surface to volume ratio will burn up more quickly than larger fuels. Thus, as large fuels ignite and burn, residence time will increase and result in a stronger heat pulse.

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Depth of Burn

Depth of burn can also be used as a fire behavior descriptor. It is simply a measure of the amount (vertical depth) the forest floor was reduced during a fire. This parameter can be expressed as the actual thickness of the layer removed, as a percentage of the total layer, or as the percentage of mineral soil exposed. Alexander (1982) states that depth of burn depends mainly on the forest floor moisture gradient and is, therefore, more or less independent of rate of spread and, thus, fireline intensity. Depth of burn is also a function of the porosity (compactness) of the forest floor. The more compressed it is, the poorer it will burn. When the forest floor is the primary fuel consumed, depth of burn is a good analog of the total heat energy released by the fire.

LINKING FIRE BEHAVIOR TO PLANT DAMAGE

Determining which descriptor(s) to use to relate fire behavior to plant damage should be done by comparing what a descriptor measures to the region of the plant affected. Is the plant part below, within, or above the flames? None of the above descriptors relates equally well to all three plant damage components. Making this determination prior to documenting a fire will assure that measurements of the needed items are taken.

Above the Flames

Byram's fireline intensity is the obvious choice for assessing crown damage. However, if flame length is used to calculate fireline intensity, numerous observations of both minimum and maximum flame length, as well as the visually perceived mode (most frequently occurring flame length) need to be taken throughout the duration of the burn. Video analysis techniques have been used to overcome many of the problems involved with visual estimates of flame length (Nelson and Adkins, in press).

Van Wagner (1973) developed an equation using fireline intensity, ambient temperature, and windspeed to predict the height of crown scorch in several Canadian tree species. This equation is commonly used prior to ignition to calculate the scorch line from the expected weather conditions and fire behavior. Comparison of this predicted height with the height of the stand to be burned will give a good indication of expected crown damage if the resource manager conducts the burn as planned. Although not yet verified by field measurements, I suspect Van Wagner's equation overpredicts scorch height in southern pines so that anyone using it in the South will err on the safe side. Estimates of crown consumption can be taken during, or within a week or two postburn, and provide the most accurate indication of crown damage, provided the plants are in leaf at the time of the burn.

In tall shrubs and trees, a portion of their stem(s) is usually above the flames. Even though the bark thins as one proceeds up a plant stem, any heat injury to the stem will probably take place within the flame zone because of the greater concentration of heat impinging upon this lower portion. Although the literature contains examples of the height of bark char correlated to plant damage, this is a poor indicator and should only be used in those cases where attempts are made to reconstruct fire behavior months later, after the scorched foliage, and foliage on fire-killed branches, has fallen (Wade and Johansen 1986).

Within the Flame Zone

In those cases where plant crowns are completely engulfed by flames, all foliage and exposed buds will be killed and no fire behavior descriptor is needed to predict crown damage. If the root system is not heat killed, the plant may survive if it is able to sprout either from the roots or the bole. Many understory shrubs have this capacity but among trees, this is exemplified in an introduced species, Melaleuca quinquenervia (Wade 1981).

When just the lower stem is subjected to flames, the choice of descriptors becomes less clear. Bark thickness is independent of fire behavior, and fire temperature within the flame zone can be assumed to be constant. Although this is not actually true, especially for low, thin flame zones, it is likely that the length of time the stem is exposed to convective heat from the flame zone rather than radiant heat becomes the factor of concern. Reaction intensity fulfills this criterion, but residence time by itself is probably a better predictor. Both of these descriptors are more strongly correlated with basal stem damage than flame length or fireline intensity.

Below the Flame Zone

Belowground meristem damage, whether to the root cambium and tips or to the root crown of herbaceous plants such as bunchgrass, requires a measure of the downward flow of heat. Combustion behind the flame front becomes more important when considering belowground damage and measures of total heat release rather than intensity should provide the desired information. Depth of burn and heat release per unit area are two good indicators of the downward heat flux. The lower layer of duff or humus is a good insulator and, thus, is an effective barrier to the downward transmission of heat. Moisture in these layers also has to be evaporated before they can be heated to ignition temperature. Some of this gaseous water vapor moves downward where it further complicates the prediction of lethal time-temperature patterns. It is a generally accepted fact that prescribed backfires consume more of the forest floor than do headfires although results to the contrary can be found.

When a burn results in complete consumption of the forest floor, preburn depth becomes an important consideration. In those fuel types where only a thin layer of dead combustible material accumulates or where the organic mantle has been recently removed (e.g., by fire), even very low-intensity fires will consume this fuel layer and the amount of available aerial fuel will determine the heat flux reaching the soil surface. As well as descriptors of fire behavior, estimates of the weight of herbaceous fuel, live and dead crown material, and standing stems that are consumed become prerequisites to the meaningful assessment of fire effects.

SUMMARY

Several fire behavior descriptors are necessary to assess the full array of fire impacts on vegetation. Rothermel and Deeming (1980) recommend the use of fireline intensity and heat per unit area for correlating fire behavior with effects but they do not specify when one or the other should be used. I recommend Byram's fireline intensity for correlating fire behavior with fire effects above the flame zone. A mathematical solution has been described to extend fireline intensity from an estimate of the rate of heat release per unit length of fire front to encompass the whole perimeter of the fire front (Catchpole and others 1982). Fireline intensity, however, is not a good indicator of what is taking place within the flame envelope or beneath the combustion zone. Reaction intensity and residence time should both correlate well with fire effects resulting from flame contact. Reaction intensity has to be calculated from other variables whereas residence time can be both easily and directly measured. When belowground effects are of interest, either heat per unit area or depth of burn can be used. A number of alignment charts and nomographs have been developed that allow a person to easily switch from one fire behavior descriptor to another (e.g., Albini 1976, Andrews and Rothermel 1982).

It should be remembered that even though two fires might have the same fire descriptor value, the effects produced may be dramatically different. This can be caused by several factors including: (1) the output values are only as good as the input values, (2) different combinations of intensity descriptor input variables can yield the same output value, (3) the variability inherent in most fires may make the mean value of a descriptor a poor indicator of fire effects, and (4) prefire and postfire conditions such as plant vigor and the incidence of insect and disease attack may vary.

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